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A Method for Analyzing High Resolution, Time Domain, Streak Camera Calibration Data

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ABSTRACT

Many experiments that require a highly accurate continuous time history of photon emission incorporate streak cameras into their setup. Nonlinear recordings both in time and spatial displacement are inherent to streak camera measurements. These nonlinearities can be attributed to sweep rate electronics, curvature of the electron optics, the magnification, and resolution of the electron optics. These nonlinearities are systematic; it has been shown that a short pulse laser source, an air-spaced etalon of known separation, and a defined spatial resolution mask can provide the proper image information to correct for the resulting distortion. A set of Interactive Data Language (IDL)[1] software routines were developed to take a series of calibration images showing temporally and spatially displaced points, and map these points from a nonlinear to a linear space-time resultant function. This correction function, in combination with standardized image correction techniques, can be applied to experiment data to minimize systematic errors and improve temporal and spatial resolution measurements.

Keywords: streak camera, time domain, calibration, IDL, analysis, temporal, spatial

1. INTRODUCTION

This paper highlights the aspects of the methodology that pertain to the collection of a unique calibration data set, image processing, image analysis, and quantitative analysis evaluation. Streak cameras have evolved into valuable tools for measuring high-bandwidth, single-shot transient events. Due to the nature of the implied resolution requirements that make a streak camera such a valuable tool, it becomes necessary, and at times very difficult, for an experimenter to discern between desired experimental results and systematic streak camera behavior that is depicted in the recorded data.

Requirements for a unique streak camera calibration methodology were established to allow an experimenter to extract their desired experimental results from the raw streak camera image output with a high degree of confidence and accuracy. This methodology involves the use of an appropriate resolution mask and a short pulse laser source to characterize the unique spatial and temporal attributes intrinsic to any particular streak camera system. In most cases, if the input and output to the system are adequately described, a corresponding transfer function can be generated to correct for spatial and temporal nonlinearities in streak camera system performance.

2. CALIBRATION SETUP AND PROCEDURES

In order to characterize the attributes of a streak camera system, a data set must be generated to describe both temporal and spatial features to within a fraction of the resolution of that system. Many applications require that the time base be known to better than two percent.[2] To do this accurately, the techniques applied must be highly reproducible and designed to emphasize the streak camera system limitations rather than particulars of the setup used to characterize the streak camera system. Putting the onus on the streak camera system is accomplished by setting up the calibration to generate higher spatial and temporal characteristics than the streak system can measure.

Defining a temporal and spatial coordinate system that adequately describes a streak camera system and all its nonlinearities is a complex task. The key is to have a precise understanding of the parameters being used to define the temporal and spatial coordinate system under evaluation.

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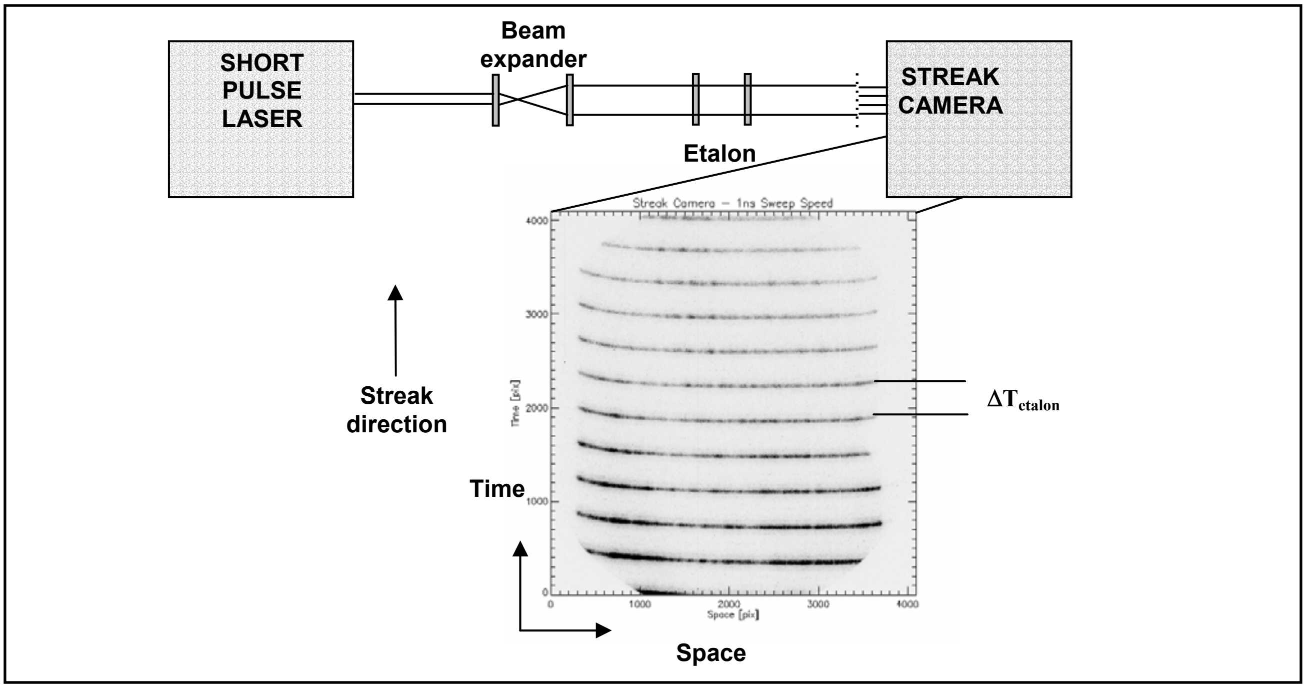

Fig. 1. Representative image depicting temporal markers taken during streak camera calibration

To define the temporal coordinate system, temporal markers are generated using a 150fs short-pulse laser directed through an air-spaced etalon of known separation. A narrow slit is installed in front of the streak camera photocathode to limit the resultant temporal image width, generated by each impending pulse from the laser, to reveal the limitation of the streak camera's temporal resolution. Figure 1 is representative of data acquired using this method. The information obtained from this data is discrete in the temporal axis but continuous in the spatial dimension. To adequately describe the spatial and temporal characteristics of the system, discrete spatial points must be defined as well.

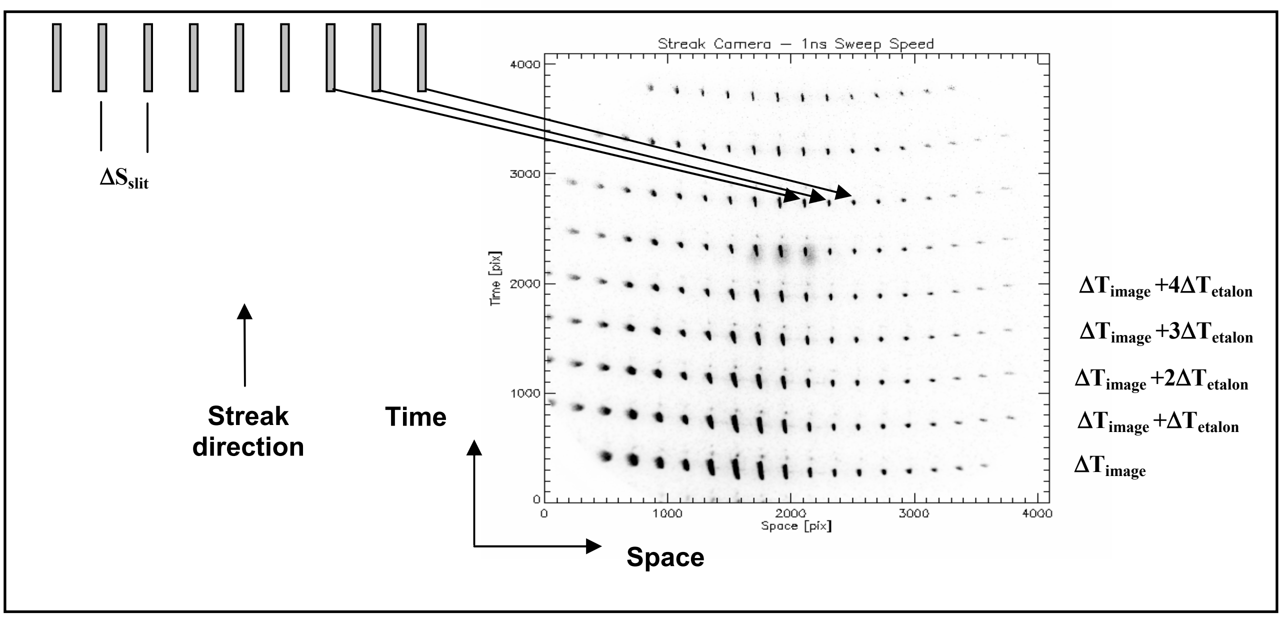

Fig. 2. Representative image depicting temporal and spatial markers defined by combined resolution mask

The solution is to incorporate a spatial resolution mask of known dimension, placed in front of the narrow slit that defines the temporal markers. A resolution mask was designed such that the combination of two masks provide enough points with temporal and spatial locations relative to the photocathode to adequately describe the temporal and spatial coordinate system of the streak camera system. Figure 2 is representative of data acquired using the combined resolution mask, where ΔS_{slit} represents a known spatial separation that defines the spatial coordinate system.

Ideally, a single image with sufficient space-time markers can adequately describe the streak camera system being evaluated. However, it was found that space-time markers need to be separated by better than ten times the system's spatial and temporal resolutions in order for automated software routines to identify the space-time markers. To increase the number of space-time markers in light of this limitation, a set of images is taken, each with a discrete temporal offset that is varied by adjusting sweep circuit trigger timing relative to the short-pulse laser signal. The resultant data set provides the necessary statistics to adequately describe the streak camera system's temporal and spatial behaviors.

3. IMAGE PROCESSING

Image processing is done using a Graphical User Interface (GUI), written in the Interactive Data Language (IDL)[1], which allows the user to input the data and set the output path for the corrective transformation matrices. This GUI allows multiple file input and does all the processing transparent to the user. Minimal user interaction is needed to process a full data set for image analysis.

3.1 File I/O

The IDL GUI allows the user to find and select multiple data and background files for processing. The routines used in the analysis can read most image file types supported by IDL, in addition to Flexible Image Transport System (FITS) file formats.

3.2 Find peaks

Image processing is broken into two sections: find peaks and analyze. The find peaks section creates a master background from the background files input to the GUI and performs a background subtraction on every image as it is processed. Example data taken from a single etalon instance in time is shown in Figure 3.

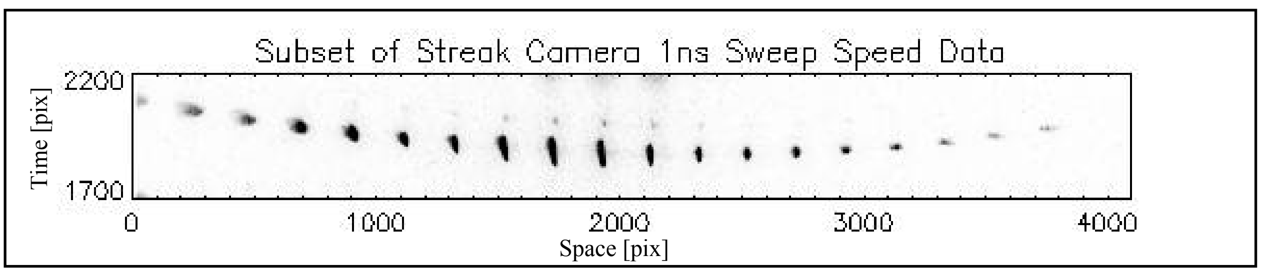

Fig. 3. Example of a resolution mask at an instance in time from a swept streak camera image.

Each image is processed individually to find the peaks of the space/time markers captured as shown here in Figure 4.

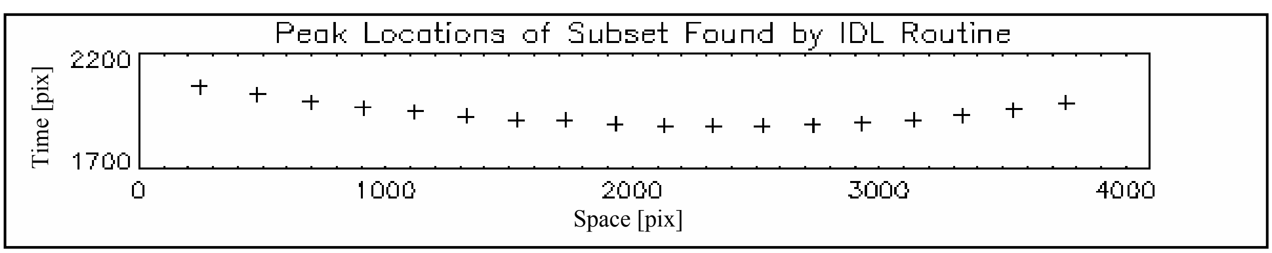

Fig. 4. Peak locations found

Once the routines find the peaks which fall within their limits, they are displayed over the image for the user to inspect. At this time, the user is prompted to add points or delete any of the points which were found due to some current software limitations. Adding and deleting points is as easy as pointing and clicking on the image. Once the user has accepted the results of the processing for that image the routines continue and apply the same methods to the rest of the data set.

3.3 Analyze

After finding all the locations of the space-time markers for the entire data set, the locations are passed to three additional routines that finalize the image processing task. First the locations are separated into time columns, which correspond to peaks that fall within a defined spatial envelope throughout the recorded time. Next each image's time columns are processed temporally to produce a corrective matrix in time according to the known temporal spacing of the etalon used. Finally, the locations are separated into space rows, corresponding to peaks of constant time. These peaks are processed spatially to produce a corrective matrix in space utilizing the known spacing of the imaged resolution mask slits. In addition, a corrected extrapolation is calculated to the edges of the data images to identify both the pixel location of the edge intercepts and the space and time that these correspond to. An example of the extrapolated fit and derived data points is shown in Figure 5.

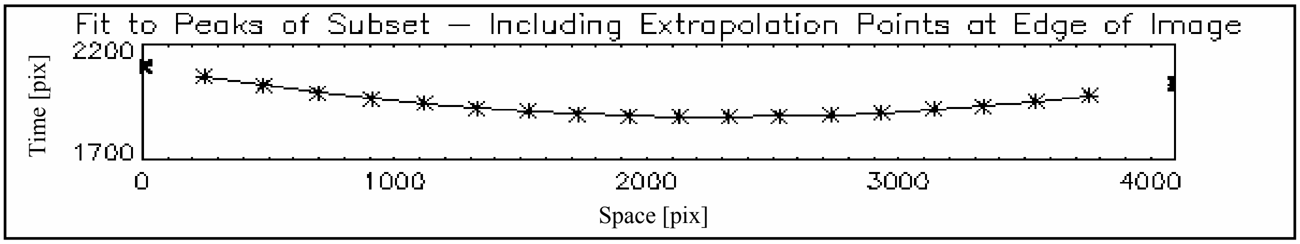

Fig. 5. Extrapolation fit and extrapolated data points

From the two step process of find peaks and analyze, four elements are produced for image analysis: original spatial location, original temporal location, corrective spatial location, and corrective temporal location.

4. IMAGE ANALYSIS

Image analysis or image correction is done utilizing routines from the IDL library for warping images. The process involves an image to be corrected and the four elements produced by the image processing routines. Figure 6 shows the result of an image corrected in both space and time utilizing the four corrective matrices produced by the image processing routines.

Without doing an analytical comparison of the uncorrected and corrected image it is visibly evident in Figure 6 that the transformation matrices make the output of the streak cameras linear in both space and time.

5. ANALYSIS EVALUATION

An analysis of how well the routines remove distortions in the spatial and temporal directions was performed. The process involved producing the corrective matrices for a data set, correcting one of the original images in the data set, and then reprocessing the corrected image. The corrective matrices produced from the already corrected image provide the data needed to estimate error in the correction routines. Figure 7 is a plot of the estimated error in time for a single image that has been corrected and reevaluated using this method. This shows the difference in time measured from the corrected image and the actual (known) time. Note that the relative timing is well known, but the absolute timing is uncertain due to jitter in the trigger system.

In the example shown in Figure 7, the RMS deviation in time is within 3ps and the spatial correction error is better than 25 microns. Both of the estimated errors are better than the spatial and temporal resolutions of the evaluated streak camera system.

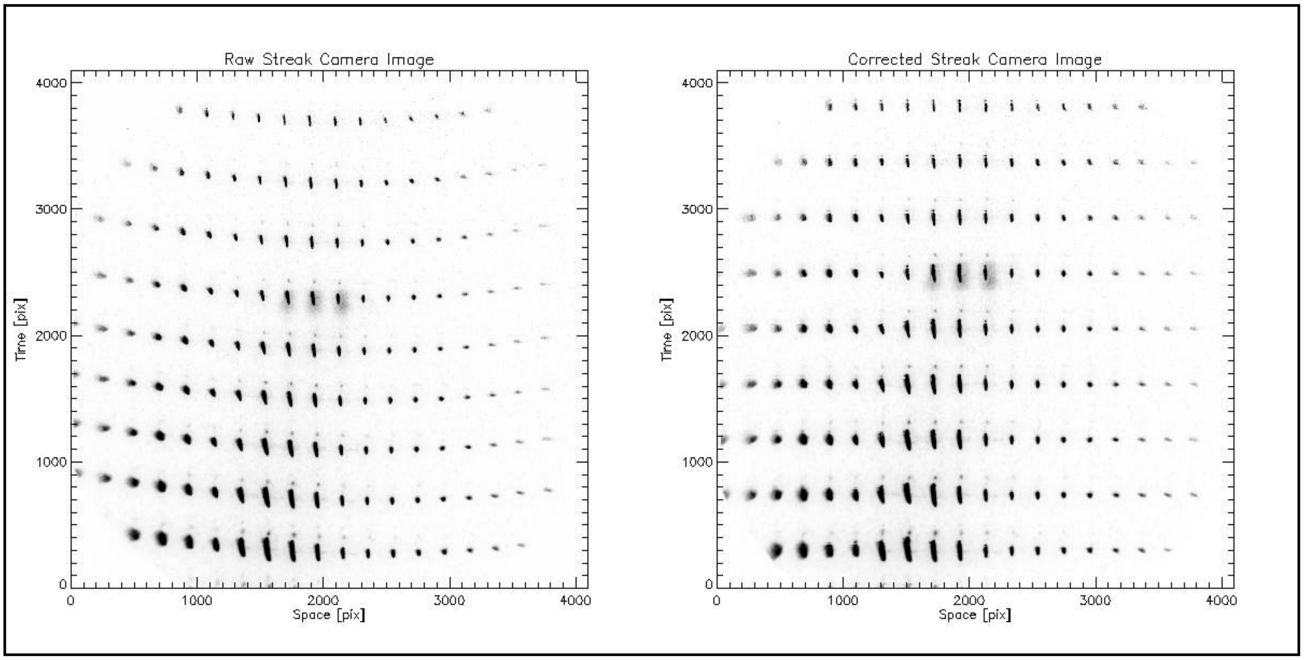

Fig. 6. Raw image and corrected image

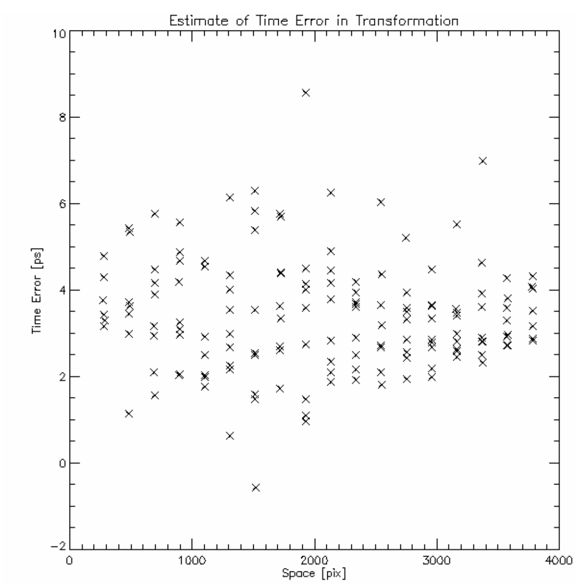

Fig. 7. Estimated error in time after correction

6. EXAMPLE APPLICATION OF CALIBRATION CORRECTION

To show that the transformation matrices generated allow an experimenter to separate the desired attributes of their data from the characteristics imposed by the streak camera system, data from a National Ignition Facility (NIF) laser timing shot was examined. The shot data consists of x-rays generated from four beam foci incident on a solid planar target imaged through a double slit, with separate filters for each slit, and onto a streak camera, as shown in Figure 8a.

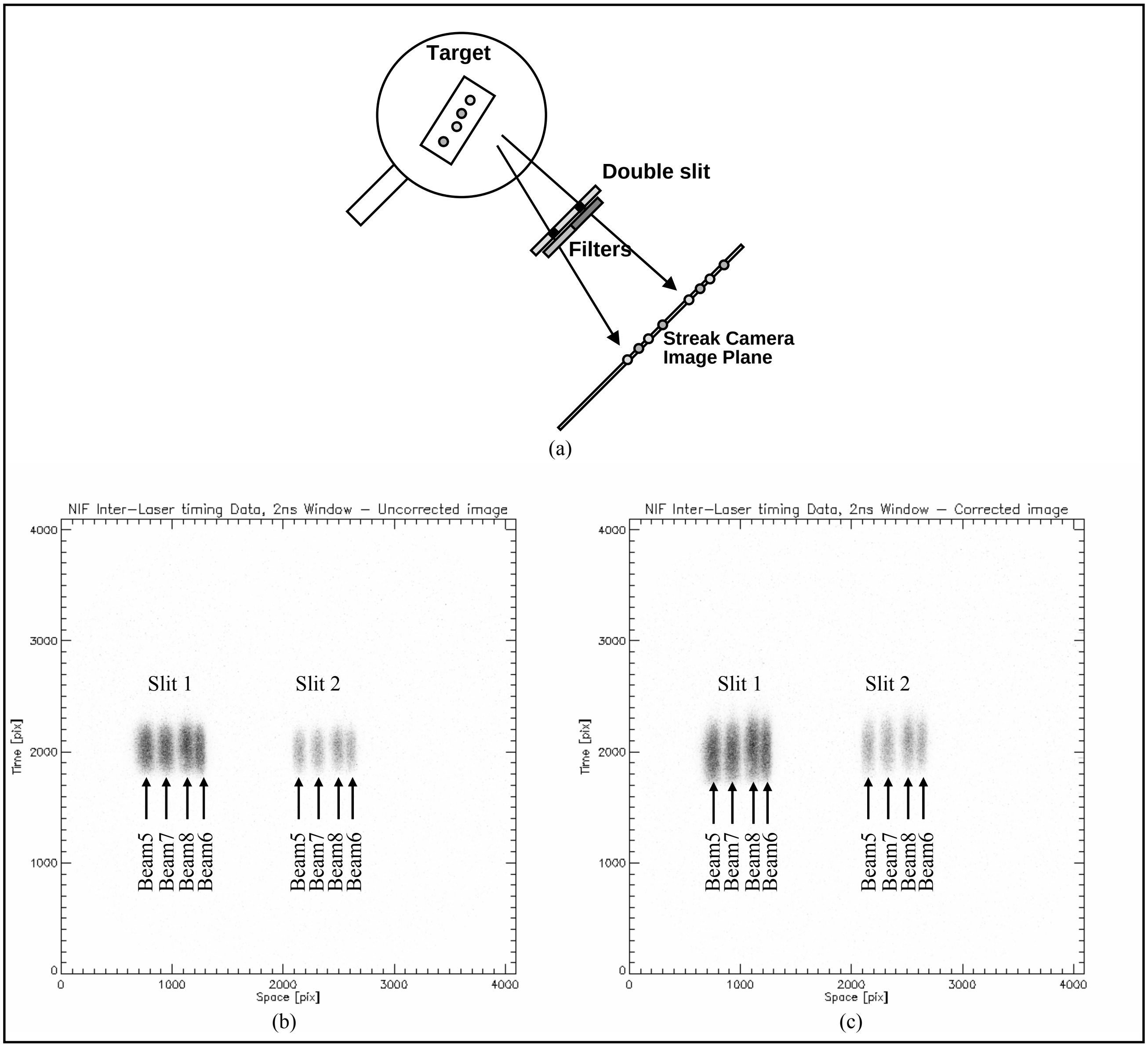

Fig. 8. NIF Inter-laser timing data (a) Experiment Setup (b) Raw data shot (c) Corrected data shot

The relative timing of the laser beams were measured taking into account setup geometry and streak camera characteristics. The analysis method previously described will correct for the streak camera's contribution to the resultant image. Figure 8c shows the image in Figure 8b corrected using the transformation matrices derived for the streak camera system which took the data. Figures 9a and 9b show Gaussian fit profiles from individual beam line outs from Figures 8b and 8c.

It is evident from Figure 9 that correcting the image in space and time shifts the measured relative timing of the beams. In this case, there is up to an 18 ps shift due to the streak camera corrections. The geometry of the beams incident on the target and variations in the optical path length from the target to the streak camera photocathode result in additional corrections of up to 5 ps. Both of these corrections must be properly accounted for in order to make a relative timing measurement to better than 20 ps to meet the NIF beam synchronization requirements.

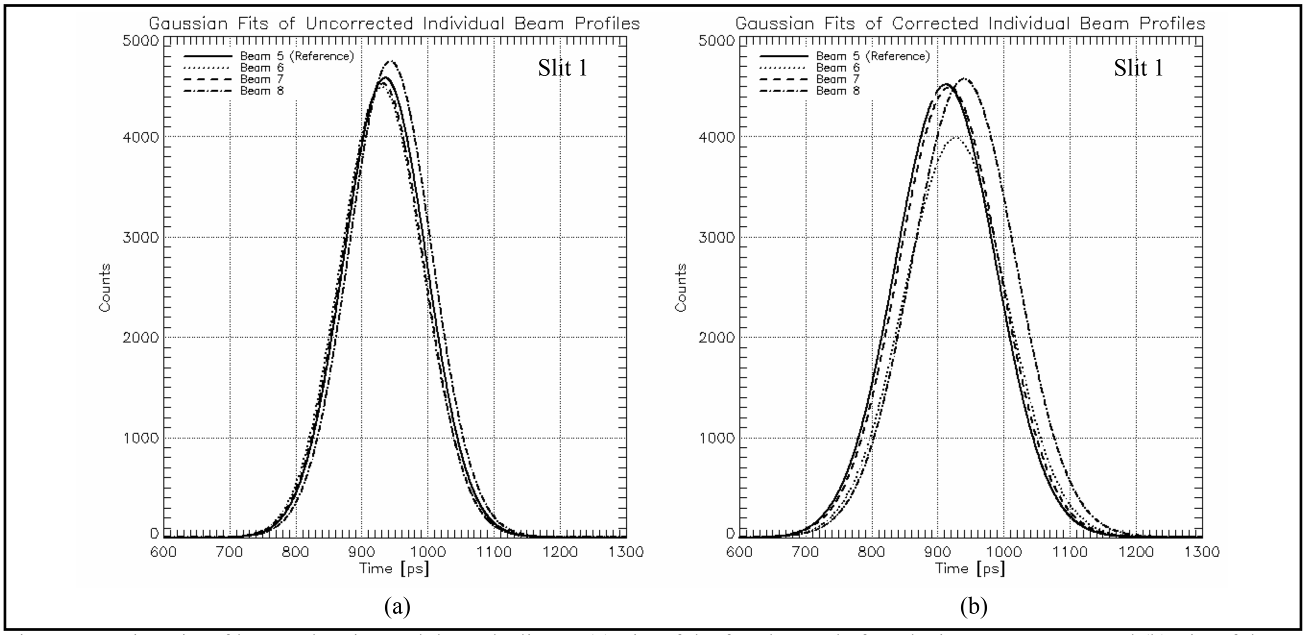

Fig. 9. Gaussian Fits of laser pulses imaged through slit one (a) Fits of the four beams before the image was corrected (b) Fits of the four beams after the image was corrected

CONCLUSIONS

A thorough understanding of a streak camera system can be gained using a well characterized space-time input. A function can be developed to accurately describe the streak camera system's influence on the resulting data. By way of this function, the nonlinear space-time contributions made by the streak camera system can be normalized out of an experimental data set. The correction has been demonstrated using quantitative error analysis techniques and through application to real experimental data sets.

Significant effort was put into characterizing streak camera system's temporal and spatial nonlinearities. Using a function that describes these nonlinearities can be used to force the output of the system such that it becomes linear, is a valuable tool to use when analyzing experimental data. Additional corrections to account for spatial and temporal flat-field effects are also important. As streak camera units are developed to measure higher bandwidth events, the techniques to generate a comprehensive space-time coordinate system to adequately describe the streak camera system will become more complex. Techniques are currently being developed to provide this comprehensive map, not only in space/time, but intensity as well.

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